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GREENHOUSE EFFECT AND GLOBAL WARMING IN SCIENCE EDUCATION: A SYSTEMATIC REVIEW OF BRAZILIAN LITERATURE

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Abstract

In basic education in Brazil, there is often confusion concerning the relationship between the greenhouse effect and global warming. The present work evaluates the status of research on this issue. A systematic literature review (SLR) was undertaken, considering studies published between 2013 and 2024, obtained using the databases CAPES Journal Portal, Google Scholar, and SciELO. The review investigated four main areas: the origin and geographical distribution of the research, the teaching strategies employed, the most common misconceptions among students, and the pedagogical contributions of the approaches described in the studies. The analysis revealed a significant increase in publications on the subject, driven by global events and the implementation of public educational policies. The strategies most frequently employed included investigative activities and the socioscientific issues approach, with an emphasis on promoting a critical understanding of climate phenomena. However, misconceptions persist, particularly related to the inability to differentiate between the natural greenhouse effect and global warming intensified by human actions. The results highlighted the need to improve pedagogical practices and revise teaching materials, to deliver education that goes beyond rote learning and can encourage critical thinking and informed decision-making. It could be concluded that integrating science, society, and politics into teaching is essential in preparing students to face the challenges arising from contemporary climate change.
Keywords: *greenhouse effect, global warming, systematic literature review*.

Introduction

Environmental chemistry plays a crucial role in understanding the Earth's atmosphere and its importance in sustaining life. The structure of the atmosphere, consisting of different layers and the gases that compose them, is essential for temperature regulation and protection of the terrestrial environment (Brown et al., 2016). The works of Spiro and Stigliani (2008) and Presbiteris (2021) provide a description of the structure of the atmosphere and its influence

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on the planet, considering the importance of each layer in protecting against radiation and maintaining conditions suitable for life.

For a comprehensive understanding of the greenhouse effect and its role in temperature regulation, it is important to consider the electromagnetic spectrum, which includes radiation of varying wavelengths and frequencies, including ultraviolet (UV), visible, and infrared (IR) (Junges et al., 2018). The greenhouse effect, a natural process that occurs in the troposphere, is fundamental for stabilizing the temperature of the planet, making life possible. Key gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor (H_2O) are essential for trapping a portion of the heat from the sun, which is converted into infrared radiation by the Earth's surface, preventing it from escaping entirely into space (Casagrande et al., 2011; Cruz et al., 2014; Jacobi et al., 2011; Presbiteris, 2021).

Solar radiation is absorbed by the Earth and is then partially re-emitted as heat. This exchange between absorbed solar energy and emitted infrared radiation is moderated by greenhouse gases, which capture and re-radiate the energy, ensuring the thermal balance necessary for sustaining life. The efficiency of this process is due to the ability of greenhouse gases to interact with infrared radiation, absorbing the heat and redistributing it back to the atmosphere and the Earth's surface (Junges et al., 2018; Presbiteris, 2021).

A more in-depth exploration of the physical and chemical mechanisms has revealed the interaction between infrared radiation and greenhouse gases, as described by Brown et al. (2016), Junges and Massoni (2018), and Presbiteris (2021). These gases absorb specific wavelengths of infrared radiation, preventing the total loss of heat into space. This heat retention is vital, since it maintains the global average temperature at around 15 °C, which is necessary for sustaining the diversity of life on Earth.

This knowledge not only helps to clarify how the planet's climate system functions, but also reveals the need to limit greenhouse gas emissions. The rising concentrations of these gases, especially due to human activities, have enhanced the natural greenhouse effect, contributing to global warming and the associated climate shifts. Understanding of the molecular interactions underlying the greenhouse effect is crucial for informing discussions on sustainability and developing policies to combat global climate change.

Given its socio-environmental importance, teaching about the greenhouse effect and climate change is essential in science education, most notably in areas such as chemistry, physics, and biology (Lambert et al., 2011; Rumenos et al., 2021). In Brazil, the National Common Core Curriculum (BNCC) has stressed the need to address these topics, so that students can understand the environmental impacts of human activities and the importance of sustainability. According to the BNCC, the Natural Sciences curriculum should enable students to understand natural phenomena, such as climate processes and their effects, while at the same time delivering environmental education that encourages critical thinking and informed citizenship (Tavares & Novais, 2021).

It is essential to provide students with opportunities in the classroom that enable them to actively engage in acquiring the scientific knowledge needed to understand emerging socio-environmental issues. By participating in such activities, students can immerse themselves in scientific research, enhancing their critical thinking and problem-solving abilities. Silva et al. (2009) pointed out the importance of studying the greenhouse effect in basic education because it can assist students in comprehending a natural phenomenon that is essential for maintaining climatic equilibrium, as well as in understanding climate change. This type of education not only raises awareness about climate change and the impact of human activities, but also stimulates critical thinking. Furthermore, the incorporation of multidisciplinary knowledge enables students to perceive the complexity of climate systems and encourages sustainable actions.

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Although the greenhouse effect (GE) and global warming (GW) are widely discussed at a global level, there remains a gap in how these concepts are addressed in basic education in Brazil. The lack of clarity in teaching and the persistence of alternative conceptions among students indicate a need to evaluate the available pedagogical practices and educational materials. Thus, the following research problem emerges: how are the relationships between the greenhouse effect and global warming being addressed in Brazilian educational practices, and in what ways can the approaches be improved to foster a better understanding of climatic phenomena?

The aim of this study was to identify and analyze the current state of research concerning the teaching of basic education in Brazil, of the relationships between the greenhouse effect and global warming, focusing on pedagogical strategies, alternative conceptions, and the challenges encountered in elucidating these concepts.

To achieve this aim, the work was guided by the following research questions:

1) What is the origin of Brazilian research concerning teaching about the greenhouse effect and global warming in basic education?

2) What are the main teaching strategies used to address these topics?

3) What are the most common alternative conceptions identified in the literature regarding the teaching of these concepts?

4) What are the results and limitations of Brazilian studies concerning the incorporation of these topics in basic education?

Understanding the ways that Brazilian researchers are addressing these issues is essential for mapping trends, finding gaps, and identifying opportunities for future research concerning basic education.

Research Methodology

General Background

The issue of global warming and climate change occupies a central position in international scientific and policy discussions, particularly following global agreements such as the Paris Agreement in 2015 and events such as COP26, held in 2021 in Glasgow. These agreements emphasize the urgent need to reduce emissions of greenhouse gases (GHGs) and encourage critical understanding of climate issues among future generations. To this end, basic education plays a crucial role in providing the information needed for students to understand the complex interactions between the natural greenhouse effect and the human-induced intensification of global warming.

In Brazil, there has been the implementation of the National Common Core Curriculum (BNCC), which encourages the teaching of multidisciplinary topics such as sustainability and climate change. The purpose of this public policy is to help in preparing students to address contemporary environmental challenges by promoting education that goes beyond rote learning, encouraging critical thinking and informed decision-making. Consequently, it is essential to understand how topics such as the greenhouse effect and global warming are being integrated into Brazilian basic education, as part of the response to the need for global education concerning environmental issues.

Despite the recognized importance of these topics, significant gaps persist in how they are integrated and understood in schools. Misconceptions, such as confusion between the natural greenhouse effect and human-driven global warming, reveal the need to improve pedagogical practices and educational materials. A systematic review of Brazilian literature on this topic can enable the mapping of trends and the identification of research gaps and opportunities, leading to better informed and contextualized pedagogical practices.

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Therefore, given the global and local relevance of this issue, the present study analyzed the current status of research in Brazil concerning teaching about the greenhouse effect and global warming, providing insights into how these concepts are being addressed, the teaching strategies employed, and the main misconceptions observed among students.

Instrument, Procedures, and Data Analysis

A systematic literature review (SLR) was performed in eight steps, as described by Akobeng (2005): (i) development of the research question; (ii) database selection; (iii) creation of the search string; (iv) performing the search and organizing the results; (v) screening articles according to inclusion and exclusion criteria; (vi) extracting relevant data; (vii) conducting a critical review of the articles; and (viii) synthesizing and interpreting the findings.

The research began with carefully formulated questions to examine how the connections between the greenhouse effect and global warming are addressed in basic education in Brazil. In the next phase, reputable academic databases including the CAPES Journal Portal, Google Scholar, and SciELO were selected based on their extensive and diverse range of publications, ensuring comprehensive coverage of relevant studies.

The CAPES Journal Portal indexes high-quality, peer-reviewed journals that are widely recognized in Brazil, providing a reliable source of information about national educational research. Google Scholar was included due to its broad indexing of various publication types. SciELO, which focuses on Latin American and Brazilian studies, provides access to regionally relevant research, allowing the inclusion of studies and methodologies specific to the desired context, which may often be absent from larger international databases. Together, these databases provided a strategically selected collection, capturing both depth and breadth in national and regional educational research, which was essential for mapping trends and identifying gaps in Brazilian basic education concerning the theme of this study.

The descriptors used to compose the search string were “efeito estufa” (“greenhouse effect”), “aquecimento global” (“global warming”), “educação básica” (“fundamental education”), “primary education,” “secondary education,” “Brasil”, and “Brazil”. The operators “OR” and “AND” were applied to create the following search string: (“efeito estufa” OR “greenhouse effect”) AND (“aquecimento global” OR “global warming”) AND (“educação básica” OR “fundamental education” OR “primary education” OR “secondary education”) AND (Brasil OR Brazil).

In the fourth stage, reference management software was used to organize the articles, facilitating subsequent analyses, ensuring the exclusion of duplicates. The fifth stage involved the rigorous selection of articles by reading abstracts and applying predefined inclusion and exclusion criteria, so that the focus was on studies relevant to the research question. Subsequently, in the sixth stage, detailed data were extracted from the selected articles, including methodologies and key findings.

In the seventh stage, critical analysis of the studies enabled the identification of trends, gaps, and opportunities for future research. In the eighth stage, the results were synthesized and interpreted, considering the implications for educational practice and policy. The limitations of the studies were also discussed, assisting the suggestion of future directions.

The year of publication, the language of the article, and the place of publication (whether the article was published solely in research journals or also in the chosen databases, excluding those articles accessible in both databases) served as exclusion criteria for the systematic review (Table 1).

This meticulous approach resulted in a detailed and up-to-date overview of how the greenhouse effect and global warming issues are addressed in basic education in Brazil. The findings constitute a significant contribution to the understanding of this topic in contemporary education.

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Table 1
Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Studies published between 2013 and 2024	Any study not published between 2013 and 2024
Articles written in Portuguese	Articles not written in Portuguese
Articles published in scientific journals	Articles not published in scientific journals
Studies focused on students in basic education in Brazil	Studies not focused on students in basic education in Brazil
Research conducted in the context of formal education	Research not conducted in the context of formal education
Articles available in the CAPES Journal Portal, Google Scholar, and SciELO databases	Articles not available in the CAPES Journal Portal, Google Scholar, and SciELO databases
Studies addressing basic education teaching of the relationships between the greenhouse effect and global warming	Studies not addressing basic education teaching of the relationships between the greenhouse effect and global warming
	Duplicate research articles

Research Results

An initial search of the databases found 589 studies (Figure 1). The selection process using restrictive keywords reduced the number to 71 potentially relevant articles. Of these, 40 articles were subsequently excluded, due to failure to meet the predefined inclusion criteria (see Table 1). Therefore, 31 articles were selected for in-depth analysis (Figure 1).

Figure 1
Results of the Systematic Review

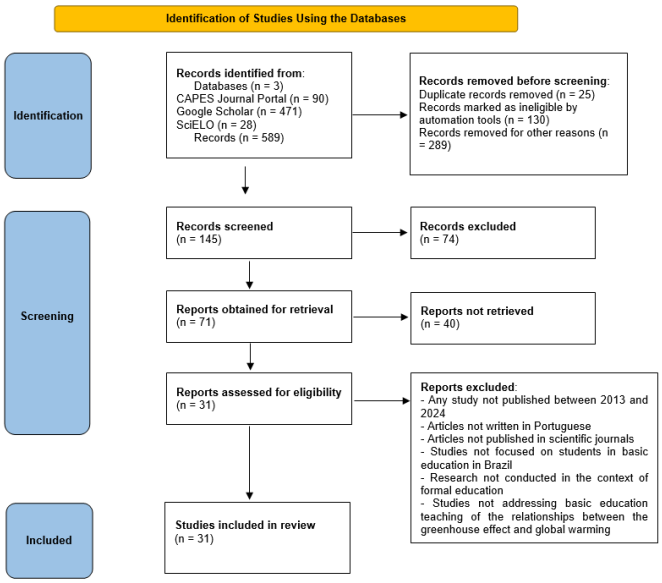

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Figure 2 shows the numbers of articles identified in the SLR, according to year of publication, concerning the relationships between the greenhouse effect and global warming, addressed in basic education. The first study analyzed was published in 2014, while the last was published in 2024. During this period, at least one study on the topic was published each year. Figure 2 also shows that there was a significant increase in the number of studies during the period from 2019 to 2023, with 21 publications (68% of the total number).

Figure 2
Number of Studies Identified in the SLR, According to Year of Publication

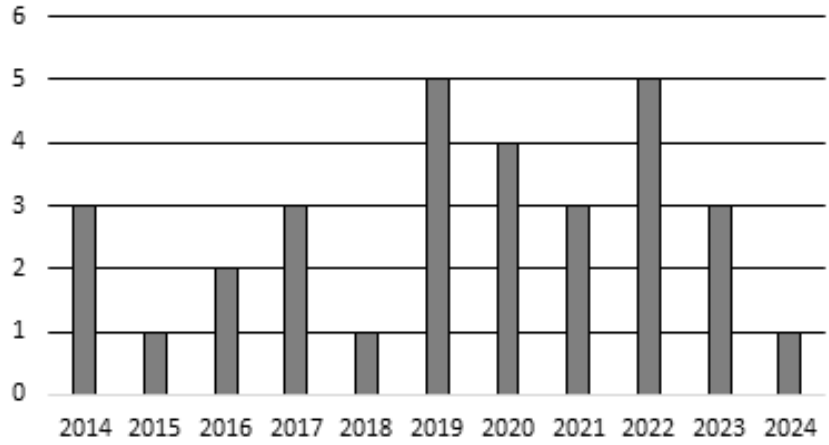

Figure 3 shows the regions of Brazil where the selected studies were conducted, together with a list of the universities where the articles were produced, evidencing the significant contribution of Brazilian public higher education institutions (HEIs) to research concerning the relationships between the greenhouse effect and global warming. All the articles were produced by researchers at federal and state public universities.

The two HEIs with the greatest number of selected studies were Federal University of Rio Grande do Sul (UFRGS) and Federal University of Minas Gerais (UFMG), with six and five studies, respectively, followed by Federal University of Pernambuco (UFPE), with three studies. Federal Institute of Santa Catarina (IFC), University of Brasília (UnB), Federal University of Piauí (UFPI), Federal University of Rio Grande do Norte (UFRN), Federal University of Sergipe (UFS), Federal Institute of Rondônia (IFRO), Federal University of Amazonas (UFAM), State University of Rio de Janeiro (UERJ), and State University of São Paulo contributed with fewer studies, ranging from one to two.

These data revealed the prominence of public universities in the production of research concerning the relationships between the greenhouse effect and global warming, since all the analyzed articles were produced by researchers at Brazilian public HEIs.

The geographical distribution of the research showed the presence of universities from different regions of Brazil, indicating a wide distribution of studies concerning the greenhouse effect and global warming. The institutions with the highest numbers of publications, UFRGS and UFMG, could be highlighted as leaders in the development of these studies.

A possible relationship could be identified between the numbers of studies and the incidence of environmental disasters in these regions. The states with the highest numbers of studies (Rio Grande do Sul and Minas Gerais) were regions with higher incidence of recent environmental disasters. This suggested that these universities might be more engaged in investigations to find solutions to environmental problems directly affecting their regions.

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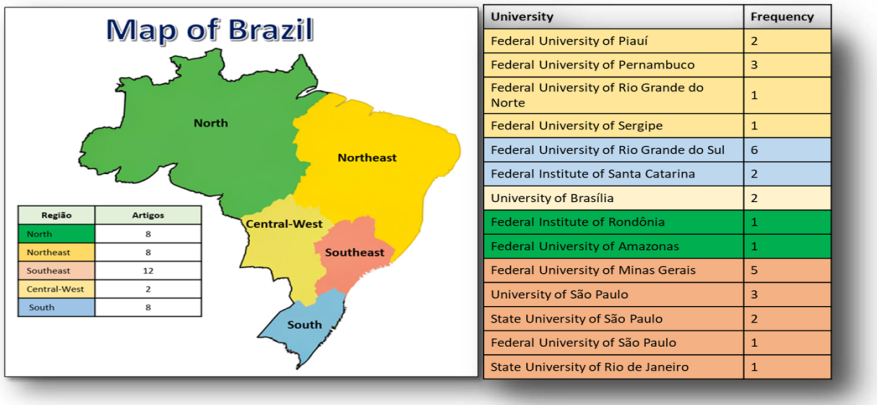
Figure 3

Map of Brazil Indicating the Numbers of Articles According to Region, and the Universities where the Studies were Performed



University	Frequency
Federal University of Piauí	2
Federal University of Pernambuco	3
Federal University of Rio Grande do Norte	1
Federal University of Sergipe	1
Federal University of Rio Grande do Sul	6
Federal Institute of Santa Catarina	2
University of Brasília	2
Federal Institute of Rondônia	1
Federal University of Amazonas	1
Federal University of Minas Gerais	5
University of São Paulo	3
State University of São Paulo	2
Federal University of São Paulo	1
State University of Rio de Janeiro	1

Teaching Strategies Addressed by the Selected Studies

Table 2 presents the teaching strategies most frequently used to address the greenhouse effect and global warming, as identified in the systematic literature review. The strategies were classified into four main categories, each with a detailed description and the corresponding absolute and relative frequencies. Analysis of the results showed that various strategies have been employed to teach concepts related to the greenhouse effect and global warming, including inquiry-based learning and socioscientific issues (45%), followed by educational games and interactive materials (26%). Pedagogical workshops and experimental activities were also widely used (19%), demonstrating the diversity of approaches adopted in teaching about the greenhouse effect and global warming.

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Table 2
Strategies Most Used in Teaching About the Greenhouse Effect and Global Warming

Category	Strategy	Description	Absolute frequency	Relative frequency (%)
Pedagogical workshops and experimental activities	Pedagogical workshops with low-cost materials	Use of accessible pedagogical workshops to teach climate concepts such as solar energy and the greenhouse effect.	6	19
	Experimental activities	Low-cost practical experiments to demonstrate the absorption of infrared radiation by gases such as CO_2.		
Educational games, interactive materials, virtual platforms, audiovisual media	Greenhouse effect games	Games that integrate various disciplines and promote environmental awareness by using questions and answers.	8	26
	Models and educational booklets, FlexQuest	Production of models and booklets to visualize and understand the scientific processes of the greenhouse effect and global warming. Use of digital platforms to mediate teaching and encourage real-world problem-solving related to global warming.		
	Films and documentaries	Use of films and documentaries to introduce and critically discuss topics related to global warming.		
STSE, socioscientific issues, and argumentation	Inquiry-based learning, socioscientific issues, and STSE	Investigative activities in which students build scientific knowledge, with teacher mediation. Use of argumentation frameworks to analyze and refute erroneous information about global warming. Role-play debates to develop argumentation skills and decision-making about climate change.	14	45
Other	Opinion surveys and textbook analysis	Studies conducted to understand the perceptions of students on the topic, and analysis of educational materials.	3	10

Among these strategies, activities involving socioscientific issues (SSI) and argumentation stood out as being most frequent, representing 45% of the practices. This reflected the value placed on investigative approaches that promote a critical and deep understanding of these complex topics.

In the study by Barbosa et al. (2012), teachers addressed the greenhouse effect and global warming using the SSI approach, focusing on the controversy about the causes of global warming. The main SSI explored was the debate between the hypothesis that global warming is primarily driven by human (anthropogenic) activities and the hypothesis attributing it to natural causes. The students were initially largely unaware of the controversial nature of the topic, prompting teachers to introduce diverse scientific perspectives. This approach involved the critical analysis of texts, together with facilitated debates, enabling students to engage with multiple viewpoints and arguments. The goal was to deepen the understanding of the students regarding the complexity of the topic, addressing both scientific evidence and the political and economic interests intertwined with it.

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Main Alternative Conceptions Identified in the SLR

A correct understanding of the phenomena of the greenhouse effect and global warming is important for critical and awareness-raising environmental education. However, several alternative conceptions (or misconceptions) persist among students, and even in educational materials. Such misconceptions can lead to incorrect understanding of the scientific processes and the socio-environmental implications of these phenomena. Table 3 lists some of the main alternative conceptions, grouped into categories, that have been identified by the reported studies, together with their descriptions and impacts.

Table 3
Main Alternative Conceptions Identified in the SLR

Category	Description	Impact
Confusion between the greenhouse effect and global warming	Many students mistakenly equate the natural greenhouse effect, which is a crucial process that helps regulate the Earth's temperature, with global warming, which refers to the unnatural increase in global average temperature caused by emissions of greenhouse gases from human activities (Oliveira et al., 2024).	This confusion can lead to an inadequate understanding of the causes and consequences of global warming, making it difficult to perceive the severity of climate change and the need for mitigation actions.
Reflection versus absorption of radiation	Some students mistakenly think that the greenhouse effect is caused only by the reflection of solar radiation in the atmosphere, failing to grasp the conversion of solar radiation into infrared radiation and its subsequent absorption by greenhouse gases (Junges et al., 2018).	This simplistic view hinders the understanding of how greenhouse gases work to retain heat in the atmosphere, underestimating the complexity of the phenomenon.
Origin and function of greenhouse gases	The discussion about greenhouse gases is often oversimplified, with an emphasis solely on carbon dioxide (CO_2), while other significant gases such as methane (CH_4) and nitrogen oxides (NO_x) are overlooked (Richter et al., 2015; Junges et al., 2018).	An incomplete understanding of greenhouse gases can limit awareness of the various emission sources and the need to control all these gases to mitigate global warming.
Inappropriate analogies with plant greenhouses	The comparison between the atmospheric greenhouse effect and the functioning of plant greenhouses is a common, but often misleading, analogy. Plant greenhouses primarily trap heat by restricting the airflow, while the atmospheric greenhouse effect operates by the absorption and emission of infrared radiation.	Unsuitable analogies can lead to misconceptions about the actual phenomenon, hindering education about the necessary measures to address global warming.
Transformation of solar radiation	Some students fail to grasp that solar radiation, which consists of visible and ultraviolet light, is converted into infrared radiation upon reaching the Earth's surface. This infrared radiation is then re-emitted, warming the atmosphere (Junges et al., 2020).	The lack of understanding of this transformation prevents a correct perception of how the greenhouse effect warms the Earth and how greenhouse gases interact with different types of radiation.
Origins of greenhouse gases	The sources of greenhouse gases are often presented in an overly simplified manner. For instance, while fossil fuel combustion is frequently mentioned, the specific sources and the processes contributing to these emissions are not always thoroughly explained (Richter et al., 2015).	Detailed knowledge about the origins of the gases is crucial for understanding which emissions can be controlled to mitigate global warming.

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This study identified several misconceptions about the greenhouse effect and global warming that persist among students, and even within educational materials. By oversimplifying or distorting the underlying scientific processes, these misconceptions have direct impacts on understanding the socio-environmental implications of the phenomena.

One of the main misconceptions concerns confusion between the natural greenhouse effect and global warming caused by human actions, leading to inadequate understanding of the causes and consequences of climate change. Another common misconception is the notion that the greenhouse effect results solely from the reflection of solar radiation in the atmosphere, neglecting the complex interactions between infrared radiation and greenhouse gases. Additionally, there is a tendency to oversimplify the origins and functions of greenhouse gases, often reducing them to carbon dioxide (CO_2) alone, without considering other significant gases, such as methane (CH_4) and nitrogen oxides (NO_x).

Furthermore, inappropriate analogies with plant greenhouses and a limited understanding of the transformation of solar radiation into infrared radiation hinder the comprehension of actual atmospheric processes. This set of misconceptions reinforces the need for educational approaches that can address these simplistic views and stimulate a more critical awareness of climate issues.

Discussion

The results of this systematic literature review highlighted the variety of pedagogical strategies developed for teaching of the greenhouse effect and global warming, as well as the persistence of alternative conceptions among students and in educational materials. The findings revealed gaps in both conceptual understanding and pedagogical approaches, representing a significant challenge in the implementation of a more critical and holistic education. These issues are discussed in depth below, from the perspectives of relevant theoretical frameworks.

The analysis revealed an increase in publications addressing the relationship between the greenhouse effect and global warming, within the context of basic education, which could be a reflection of greater awareness and actions regarding climate change. The Paris Agreement, signed in 2015, marked a historical milestone in global climate negotiations by establishing clear goals to limit global temperature rise. This international commitment may have driven a surge in research focused on global warming and its educational implications, due to the perceived need to prepare new generations to understand and address these critical issues (Oliveira et al., 2024).

Between 2018 and 2019, youth-led movements, such as the climate strikes initiated by Greta Thunberg, drew global attention to the urgency of action on climate change. These movements not only mobilized millions of people worldwide, but also influenced academia, motivating more research concerning climate change education in schools. The public awareness generated by these movements was reflected in the significantly increased number of publications on the subject, starting in 2019 (Marques da Silva et al., 2020).

The COP26 meeting, held in Glasgow in 2021, reaffirmed global commitments to reducing greenhouse gas emissions, further emphasizing the need for educational initiatives to address climate change. This international commitment accelerated research on climate education, including in Brazil. The implementation of educational policies such as the National Common Core Curriculum (BNCC) in Brazil, which was approved in 2017, incorporated the topics of sustainability and climate change into school curricula, leading to a rise in academic production focused on climate education.

Educating students about climate change and the greenhouse effect is essential for the development of responsible citizens capable of making informed decisions and contributing to a sustainable future (Neris et al., 2022). By integrating these themes into the school curriculum,

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future generations can be prepared to face complex environmental challenges and become agents of change in their communities. This is a crucial aspect of the current demand for a more critical scientific education.

As studies such as that of Neris et al. (2022) suggest, achieving these educational goals requires methodologies that encourage the development of critical thinking about climate change and the greenhouse effect, helping students to recognize that science involves uncertainties and ongoing debates, especially in the case of complex topics such as global warming. The methodology adopted by Neris et al. (2022), based on theoretical-methodological aspects of the SSI approach, provided students with the opportunity to engage in critical discussions and practical activities. This involvement enabled them to consolidate scientific knowledge and develop skills in argumentation and informed decision-making.

The incorporation of SSI into teaching enables students to build scientific knowledge, counter misinformation, and develop a critical perspective on the controversies involved (Barbosa et al., 2012). This approach broadens the understanding of students about environmental issues, so that they are able to contemplate multiple perspectives and understand the intersections among science, society, and politics. In this way, the adoption of the SSI approach can deepen scientific comprehension, shifting away from the traditional view of science as static knowledge, as described by Kuhn (1989) in his concept of "normal science". Researchers such as Allchin (2013), Wong and Hodson (2010), and Irzik and Nola (2014) provide critiques of prescriptive approaches that reduce science education to declarative knowledge, suggesting that this shift in focus can enable students to acquire critical and argumentation skills. By recognizing science as a human endeavor that is subject to revisions, questioning, and historical transformations, and understanding it as a socially situated practice, students can become more actively and informatively engaged in socioscientific discussions, leading to a more conscious engagement in a society marked by scientific advances and ethical dilemmas (Ratcliffe & Grace, 2003).

This view is consistent with work highlighting the socio-environmental impacts caused by environmental degradation and technological advancement. The movement that arose from these concerns was the starting point for studies in the field of Science-Technology-Society (STS), which evolved to include the environment, resulting in the Science-Technology-Society-Environment (STSE) movement (Auler & Bazzo, 2001; Santos & Mortimer, 2002; Cavalcanti et al., 2014; Vilches et al., 2011). In recent years, discussions in education concerning SSI have become consolidated in a powerful approach for engaging students in global, regional, and local issues, preparing them for a participation that is more critical and better informed.

As pointed out by Conrado and Nunes-Neto (2018), socioscientific issues (SSI) involve complex and controversial challenges, requiring an interdisciplinary and contextualized approach that integrates scientific knowledge with ethics, history, and philosophy. This new understanding of SSI signifies a shift in addressing these topics, moving beyond simplified interpretations, to recognition of their inherent complexity. As suggested by Zeidler et al. (2016), contemporary educational reforms require greater emphasis on the nature of science and scientific inquiry, to promote critical scientific literacy that encompasses the moral and ethical dimensions essential for the development of social skills in students (Zeidler & Keefer, 2003).

In addition to the ability to make informed decisions, the SSI approach exposes students to multiple perspectives and interpretations, as in the debate regarding anthropogenic and natural causes of global warming. This approach not only delivers established scientific knowledge, but also allows consideration of the uncertainties and debates inherent within scientific discourse, preparing students for engagement in real-world scientific discussions (Conrado & Nunes-Neto, 2018).

Additionally, the use of pedagogical workshops and experimental activities, as well as educational games and audiovisual media, can strengthen links between scientific knowledge

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and the everyday lives of the students. These practices facilitate comprehension of climate processes and make complex content (as in the case of the greenhouse effect) more accessible and meaningful.

A notable example is the work of Cunha and Rodrigues (2019), who used pedagogical workshops with low-cost experimental activities to promote the engagement of basic education students with topics including the atmosphere, the greenhouse effect, and global warming. The workshops had a phased structure, beginning with problem-solving exercises to assess the prior knowledge of the students. Subsequently, the students participated in hands-on investigative experiments, such as using aluminum cans to simulate the role of the atmosphere in temperature regulation, highlighting the vital function of the greenhouse effect in sustaining life on Earth. Another experiment employed PET bottles to illustrate how increased levels of greenhouse gases contribute to global warming. The primary focus of these workshops was to clarify the distinction between the greenhouse effect, a natural and essential process for sustaining life, and global warming, which is intensified by human activities and has serious climatic repercussions. The students were encouraged to analyze both natural and human contributions to global warming and its consequences. These activities led to a deeper and more critical understanding among the students, enhancing their scientific knowledge, argumentation skills, and awareness of the importance of mitigating the negative impacts of global warming.

However, it is important to recognize that during the learning process, students may develop alternative conceptions. Identifying and addressing misconceptions is crucial for ensuring that scientific concepts are correctly understood. The next section explores the main alternative conceptions identified in the SLR and their implications for science education.

Given the increasing frequency of climate-related disasters such as floods, droughts, and heatwaves, it is vital for students to develop a thorough understanding of the greenhouse effect and global warming. Teaching should extend beyond simple memorization, aiming to cultivate critical thinking ability. Students must be able to analyze information, identify alternative conceptions, and understand the socio-environmental consequences of climate change. Achieving this objective requires educational strategies that go beyond the delivery of knowledge, encouraging critical reflection and socio-environmental responsibility.

A clear understanding of climate phenomena is essential to address environmental challenges. One of the most frequent misconceptions, as highlighted in the category "Confusion between the greenhouse effect and global warming", is lack of understanding of the difference between the natural greenhouse effect and human-driven global warming. Such misconceptions concerning the causes and consequences of global warming hinder recognition of the severity of climate change and the urgency for mitigation measures.

The natural greenhouse effect is a vital process that acts in regulating Earth's temperature, ensuring that the planet can support life. Greenhouse gases including water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO_x) trap some of the infrared radiation emitted by the Earth's surface, maintaining the global average temperature at around 15 °C. This process is essential to prevent the planet from freezing. Knowledge about its mechanisms is essential for understanding the climate equilibrium of the Earth and the environmental impacts associated with global warming, as discussed by Casagrande et al. (2011), Cruz et al. (2014), Presbiteris (2021), and Jacobi et al. (2011).

The situation becomes more complicated as the concentrations of greenhouse gases increase because of human activities, with the burning of fossil fuels, deforestation, and intensive agriculture being the primary contributors to such increases. Anthropic emissions of gases such as CO_2, CH_4, and chlorofluorocarbons (CFCs) amplify the natural greenhouse effect, which has led to a global average temperature increase of at least 1.2 °C since the Industrial Revolution (IPCC, 2023). This warming has been associated with glacier melting, ecosystem changes, and the extinction of some species (Spiro & Stigliani, 2008; Cruz et al., 2014; Junges, et al., 2018; Presbiteris, 2021; IPCC, 2021, 2023).

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It is evident that to fully elucidate climate change, it is necessary to be able to clearly differentiate between the natural greenhouse effect and the global warming exacerbated by human activities. This distinction is a clear requirement in the implementation of effective mitigation strategies, as well as in delivering properly informed environmental education, where emphasis should be given to providing practical examples and scientific evidence to clarify the concepts and increase awareness of the severity of the climate crisis.

Another significant issue is misunderstanding concerning the reflection and absorption of radiation. Many misconceptions consider that the greenhouse effect is solely caused by the reflection of solar radiation in the atmosphere, without recognizing the conversion of solar energy into infrared radiation and its subsequent absorption by greenhouse gases.

As described by Lacis et al. (2010) and Junges et al. (2018), from physical, chemical, environmental, and geographical perspectives, this process is more complex than the simple absorption of solar radiation by the Earth. The planet cannot absorb all the energy received from the sun, since this would lead to surface overheating. Instead, the Earth must re-emit part of the absorbed energy back into the atmosphere. However, if all the energy was to be re-emitted, there would be insufficient heat retention, resulting in a cooling effect. Therefore, to regulate the Earth's temperature, it is essential to ensure a balance between absorbed and re-emitted energy. This balance is predominantly maintained by the greenhouse effect, with atmospheric greenhouse gases trapping some of the heat re-emitted by the Earth, preventing it from fully escaping into space.

Greenhouse gases play a crucial role in the greenhouse effect, since their presence in appropriate amounts contributes to regulating the average temperature of the planet by the conversion of radiation. In this process, the solar energy absorbed by the Earth's surface is re-emitted as infrared (IR) radiation, or heat. Part of this infrared radiation is absorbed by greenhouse gases in the atmosphere and is then re-emitted in multiple directions by the gas molecules. Consequently, heat is retained in the atmosphere, maintaining the temperature of the planet at a level suitable for sustaining life (Presbiteris, 2021; Spiro & Stigliani, 2008).

It is essential to understand how infrared (IR) electromagnetic radiation interacts with greenhouse gases, according to the principles of physical chemistry. Solar radiation reaching the Earth is composed of ultraviolet (UV) radiation and visible light, which is absorbed and then re-emitted as IR radiation (Junges et al., 2018).

A common misconception is the analogy between the atmospheric greenhouse effect and the way that a plant greenhouse functions, which can be both inadequate and misleading. Plant greenhouses primarily function by restricting airflow, creating a confined space where heat is retained due to a physical barrier that limits air circulation, causing the internal temperature to be higher than that of the external environment (Bertoni & Lombardo, 2005).

The atmospheric greenhouse effect, on the other hand, involves complex processes in which greenhouse gases (H_2O, CO_2, CH_4, and others) absorb and emit infrared radiation within the atmosphere (Junges et al., 2018; Lacis et al., 2010). These gases allow solar radiation to pass through the atmosphere and heat the Earth's surface. The infrared radiation that is subsequently emitted by the surface is then partially absorbed and re-emitted in different directions by the greenhouse gases, trapping heat within the atmosphere (IPCC, 2021).

Perceiving this distinction is crucial for accurately understanding global warming, since the atmospheric greenhouse effect is governed by the chemical makeup and radiative interactions of these gases, whereas plant greenhouses operate by controlling airflow using physical barriers. Although the analogy may assist in introducing the concept of heat retention, it takes little account of the complex processes involved in the atmospheric greenhouse effect.

Furthermore, the sources of greenhouse gases are often discussed in an overly simplified manner, which can hinder a full understanding of the processes and specific origins. For example, fossil fuel combustion is frequently cited as a major source of carbon dioxide (CO_2), but the specific sectors contributing to the emissions are often overlooked. Major sources

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include electricity generation from coal and natural gas, transport (road, air, and maritime), and the cement industry, all of which contribute significant CO_2 emissions (IPCC, 2021).

The sources of other greenhouse gases, such as CH4 and NOx, are often underestimated. For example, large amounts of CH_4 are emitted from agriculture, especially due to enteric fermentation in ruminants, as well as from anaerobic decomposition in landfills (EPA, 2021). Emissions of nitrogen oxides are primarily associated with the application of nitrogen fertilizers in agriculture and the combustion of fossil fuels in vehicles and power plants (Davidson, 2009).

A thorough understanding of the sources of greenhouse gases necessitates an in-depth evaluation of the diverse human activities and industrial processes that contribute to their emissions. This knowledge is crucial for developing effective mitigation policies and encouraging sustainable practices that can lower the concentrations of these gases in the atmosphere (Spiro & Stigliani, 2008). Ignoring the complexity of emission sources can result in inadequate and ineffective strategies to combat climate change.

The findings of the present SLR emphasize the need for a well-founded and critical educational approach to address the misconceptions of students concerning climate change. Confusion between the natural greenhouse effect and global warming, as well as limited understanding of greenhouse gases and the radiative processes involved, indicate that greater clarity is required in the scientific content presented in classrooms and educational materials. Promoting education that goes beyond the memorization of concepts, encouraging critical thinking and reflection on the interactions among science, society, and politics, is essential to form citizens capable of facing the challenges posed by climate change. For this purpose, pedagogical strategies such as the SSI approach show excellent potential, enabling students to understand the complexity of environmental issues and develop the ability to make informed decisions based on scientific data.

Conclusions and Implications

The increasing occurrence of large-scale natural disasters, such as the recent devastating floods in Spain and Brazil, as well as recurring wildfires in Brazil and elsewhere, suggests a clear connection between these extreme events and climate change. These types of disasters not only expose the vulnerabilities of communities, but also indicate the urgent need to integrate these issues into basic education. The present research adds value to the field by highlighting the importance of methodologies that go beyond the teaching of scientific concepts, emphasizing a commitment to transformative, emancipatory, and socially engaged education.

Given the existence of undeniable data concerning climate change and its impacts, it is essential to develop a more critical scientific education. In basic education, this requires the adoption of interdisciplinary approaches that can link local issues to global challenges, allowing educators, even in resource-limited contexts, to develop curricula aligned with experienced realities. In this way, students can be enabled to view local and global events as integral parts of their daily lives and collective future. This type of education not only empowers students to understand natural phenomena, but also prepares them to become agents of transformation in their communities.

The implications for pedagogical practice are clear: it is essential to adopt educational approaches that can promote critical debate and enable students to make informed decisions. Educational policies must give value to environmental education that is critical and reflective, integrated into a comprehensive strategy to prepare the next generations for a sustainable future. This research contributes by highlighting critical points and opportunities for improvement in the teaching of socio-environmental topics, connecting science to the daily lives of school communities. Guidelines are offered for the development of didactic-pedagogical practices that encourage the critical examination of local and global realities.

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Declaration of Interest

The authors declare no competing interest.

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